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PROBLEMS INVOLVED IN DEVELOPING AN INTEGRATED FLIGHT CONTROL SYSTEM WITH EMPHASIS ON CURVED FLIGHT PATH PROFILES

H. Boehret

Translation of: "Realisierungsprobleme eines integrierten Flugregelungssystems unter besonderer Beruecksichtigung gekruemmter Flugbahnprofile." DGLR Paper 73-030, presented at Symposium on New Approach and Landing Techniques, May 2-4, 1973, in Duesseldorf.

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16. Abstract The integrated flight control system, FRG 70 is built according to the principle of COMPLETE feedback provides for the requisite passenger comfort and control characteristics. It is superior to conventional flight controllers (autopilot and thrust controller), especially during steep approaches. This paper presents the design principles, operating characteristics, application to direct lift control (DLC) and requisite pilot displays.

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PROBLEMS INVOLVED IN DEVELOPING AN INTEGRATED FLIGHT CONTROL SYSTEM WITH EMPHASIS ON CURVED FLIGHT PATH PROFILES

H. Boehret

Summary /1*

Curved steep approaches pose high requirements on flight control systems. The trajectory must be accurately maintained and the aerodynamic flow condition must be exactly controlled at the same time. The thrust must be relatively constant and sufficient passenger comfort must be provided.

The integrated flight control system FRG 70 is built according to complete state feedback principles. The controlled variables are strongly coupled and are directed back to the elevators and the thrust level. This principle becomes possible by restricting oneself to the important state variables. The flight control system is characterized by exactly maintaining the aerodynamic flow state while providing a high degree of passenger comfort. The exact trajectory control is supported by a thrust control which depends on the trajectory angle, which allows a quiet thrust level.

Because of the coupled switching of the state variables, the integrated flight control system FRG 70 is considerably better than conventional controllers, which consist of autopilot and forward thrust controller. The difference becomes very apparent

*Numbers in the margin indicate pagination of foreign text.

for curved steep approaches. The properties of the integrated system were proven in flight tests which consisted of more than 500 automatic approaches and landings. Some improvement can be obtained by the direct lift control and by using an electronic monitor display.

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1. Introduction

New types of approach procedures are required for STOL aircraft, in order to land on air fields located in populated regions. The approach profiles must be steep in order to fly over obstacles in a safe way and in order to hold the noise level as low as possible. In order to reduce the noise, steeper approach methods are being investigated for approaches to conventional airports. The search for suitable approach trajectories leads to non-rectilinear profiles, so as to fly into the guide beam system without overshoot and so as to be able to decrease the high descent velocities in the vicinity of the ground at the right time. Figure 1 gives a typical example of such an approach profile. It consists of four elements. During the first element, the approach directed by the guide beam occurs at an constant altitude, to provide for simple intercept. During the second phase, there is a transition from horizontal flight to steep approach along a parabolic arc. This parabolic arc is tangential to the steep straight third element. The possible steepness of this element depends on the type of aircraft. However, it cannot be radial with respect to the guide beam system, in order to be able to transfer to the fourth element along another parabolic arc before pullout to the flatter trajectory angles occurs. This means that the high descent velocities in the vicinity of the ground which occur during steep approaches are reduced. Because of the simple mechanization and constant vertical acceleration, parabolas were selected as transfer elements between the straight line segment of the nominal trajectory. The profile given in Figure 1 was designed so that the vertical accelerations caused by curvature were 0.2 m/sec^2 at a maximum. This value is so low that a high degree of passenger comfort is provided. /3

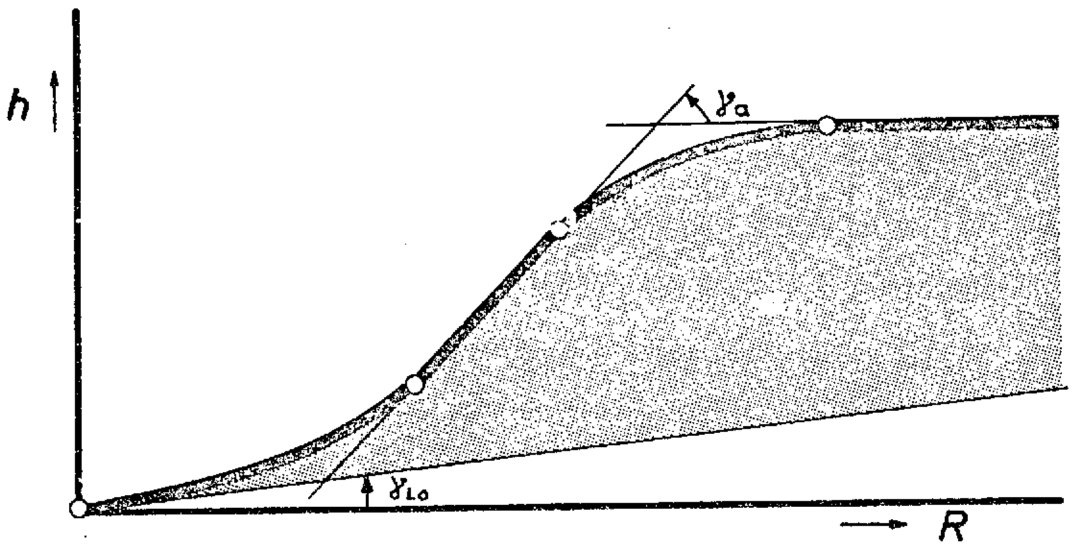

Figure 1. Curved steep approach profile.

In the case of approach to short landing fields, the touchdown point must be selected accurately and the flight trajectory velocity must be as small as possible. This requires an exact control of the aerodynamic flow state for high lift coefficients. The flight trajectory polar shows that an aircraft can approach more steeply, the slower it flies. This is why, /4 during the steep approach, the C_A value must be held constant [1]. Figure 2 shows the commanded C_A value variation. During this transition to flatter trajectory angles at the end of pullout, the C_A value can be increased so as to reach its maximum nominal value for the touchdown during the pullout. This nominal value variation makes possible steep approaches with sufficiently large safety margin with respect to the flow separation velocity.

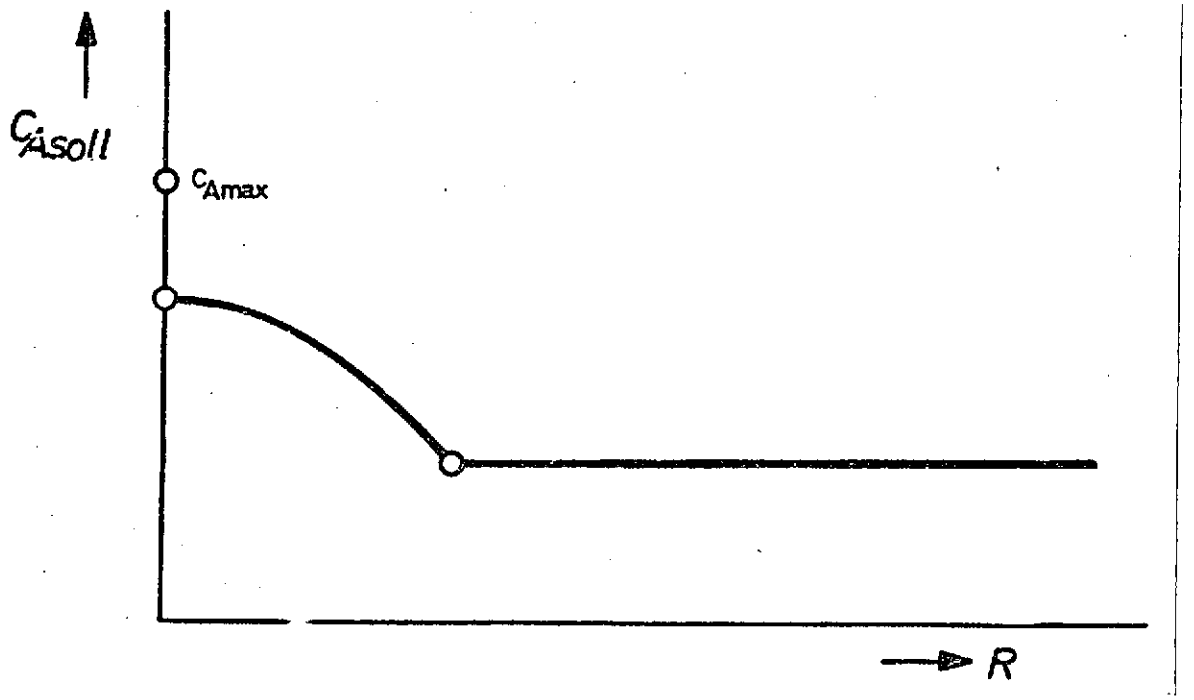

Figure 2. Commanded C_A value variation.

Both problems, the control of the aerodynamic flow state and the control of the flight trajectory for curved steep approaches, require a high degree of pilot skill. The aerodynamic properties of an aircraft deteriorate with increasing C_A values. In order to exactly maintain the flight trajectory, he has to adjust the elevator as well as the thrust continuously. Under poor weather conditions and for dense flight traffic, he is no longer capable of manually carrying out approach and landing with any degree of certainty. From this emerge the requirements for a flight control system which very accurately controls deviations from the nominal flight trajectory and deviations from the nominal aerodynamic flow state.

2. Structure of the Integrated Flight Control System FRG 70 /5

The basic structure of a suitable flight control system has been, for the most part, specified by modern control theory.

Assuming a linear control system with constant coefficients, total feedback of all state variables to all of the available control variables leads to optimum control properties.

In order to exactly control the flight trajectory and the aerodynamic flow state, in the integrated flight control system FRG 70, we made the deviations of the flight trajectory from the commanded flight trajectory profile as small as possible, as well as the deviations between the lift coefficient from its nominal value. Usually two independent control variables are required to independently control these two controlled variables. In the case of conventional aircraft, these are the elevators and the gas throttles for the engines. Figure 3 shows the block diagram of such an integrated flight control system. All of the important states are determined from the output signals of the sensors, through observation filters. The feedback matrix switches these states back to the elevator and the thrust in a highly coupled manner.

Depending on the approach element, the state of the altitude is established using a barometric altimeter. Or this can be done from data from the guide beam receiver, or it can be done by the radar altimeter. The aerodynamic flow state is measured by the angle of attack.

3. Design Criteria of an Integrated Flight Control System /6

A control system always represents a compromise among competing requirements. In the present case, there is a requirement for having the deviations between the commanded flight profile and the prescribed angle of attack nominal value be as small as possible. In the case of a flight control system for approach and landing, one must also make sure that the activity

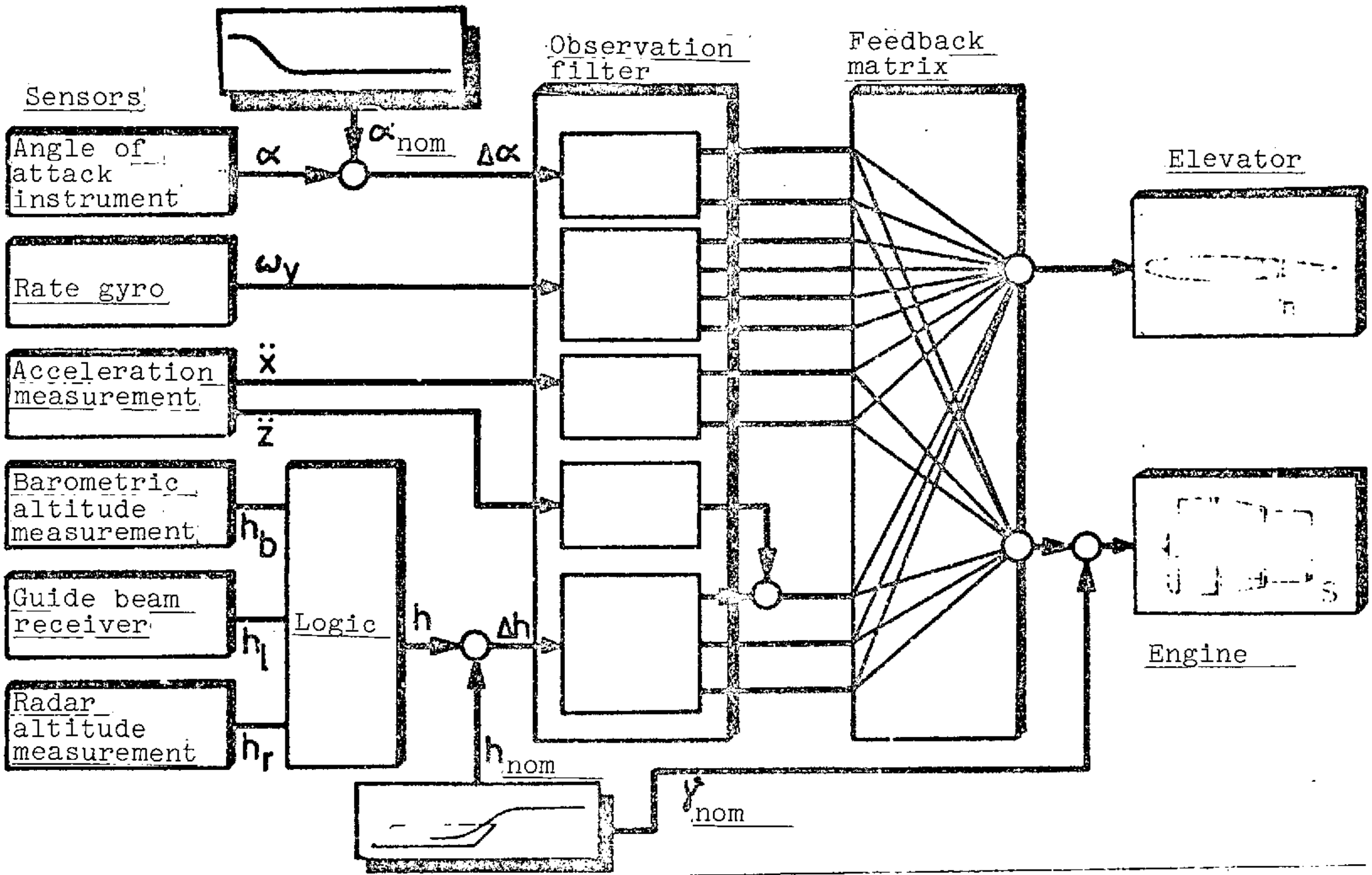

Figure 3. Block diagram of an integrated flight control system FRG 70.

of the gas throttles is as low as possible. Thrust noisiness is produced by the fact that the controlled deviations adjust the thrust at a high frequency under gusty conditions. The passengers and the inhabitants of areas near airports are disturbed more by a continuously changing thrust level than by a constant engine noise, having the same intensity. In addition, unquiet thrust variations reduce the lifetime of the engines and increase the fuel consumption. There must be a sufficient degree of passenger comfort in addition to quiet thrust variation. The pitch angle rates and the vertical accelerations cannot be too large.

The investigations show that the requirements contradicted each other by pairs. On the one hand, trajectory guidance accuracy and quiet thrust conditions are contradictory. On the other hand, the angle of attack accuracy and passenger comfort were found to be contradictory. Starting with the requirements mentioned above, it is possible to determine the quality of the control system by means of a quality criterion. The relationship of the individual requirements with respect to each other is then specified by evaluation factors. These evaluation factors specify, for example, that an altitude deviation from 5 m, an angle of attack deviation of 0.5°, a thrust gradient of 10 Kp/sec, and a pitch rate of 0.5°/sec will have the same detrimental effects.

The definition of this quality criterion is the reason why the parameters of the control system can be determined using an automatic optimization method. The sum of the squares of the control deviations is made a minimum in order for the require- /7
ments of the quality criterion to be satisfied as well as possible. A control system designed according to this principle is characterized by the fact that it is not sensitive to parameters. The

parameters of the control system as well as the parameters of the aircraft can change within wide limits without noticeably deteriorating the quality of the total system.

After specifying the four evaluation factors of the quality criterion, this automatic optimization method makes it possible to determine all of the twenty-four command factors and time constants of the integrated flight control system FRG 70. The evaluation factors must be defined very carefully. The investigations showed that more than the simulation results are required for this. In particular, the thrust quietness and the passenger comfort must be verified by flight tests.

During manual flight, the pilot controls the high frequency gust disturbances using the elevator, and he controls the low frequency disturbances by the thrust. This frequency division must also be maintained in the automatic system, so as to provide sufficiently quiet thrust conditions. It is not suitable to use a time delay in the control signals for the thrust, because this reduces the stability of the system. If the evaluation of the thrust quietness is increased in the quality criterion for automatic optimization, then this frequency division can be obtained by reducing the command factors of the control parameters with respect to thrust. By increasing the thrust quietness, we automatically obtain a deterioration in the trajectory control accuracy. Because of the strong internal coupling of the control system, straight line ILS approaches can be carried out with a higher degree of accuracy when the thrust quietness has a high evaluation than is the case with conventional control systems, consisting of autopilot and forward thrust controller. However, these requirements for trajectory control increase so much in the case of curved steep approaches that they can no longer be satisfied by conventional control systems. Because the thrust control depends on the trajectory angle, the integrated flight control system FRG 70 is capable of satisfying these requirements.

4. Trajectory Angle-Dependent Thrust Control /8

The following steady state relationship exists between the trajectory angle γ and the thrust:

$$S = G \left(\gamma + \frac{C_W}{C_A} \right) \qquad (1)$$

Equation (1) shows that, for a flight with constant lift coefficient and constant weight, the thrust depends linearly on the trajectory angle. Since, during steep approach, the trajectory angle changes are large, it is necessary to carry out large changes in thrust level in order to follow the trajectory profile. A control system will only provide correction signals to the actuators when control deviations are present. If the command factors are low, then larger deviations are required to bring the controlled variables from one position to the other in a steady way. In the present case, this means that the thrust reduction during transition to steep approach can only be carried out by trajectory deviations. Because of the integrated modulation of altitude and angle of attack, these deviations will be completely controlled even for shear wind conditions after a certain amount of time. The influence of integral modulations on thrust quietness is low, and it must be kept low for reasons of stability. It is possible to avoid deviations of the aircraft from the commanded flight trajectory if the steady thrust change during the curved steep approach is provided not by the thrust regulation system but by a superimposed thrust control. According to Equation (1), the trajectory angle γ is the suitable variable for thrust control. Figure 4 shows the stationary relationship according to Equation (1) between the trajectory angle and the

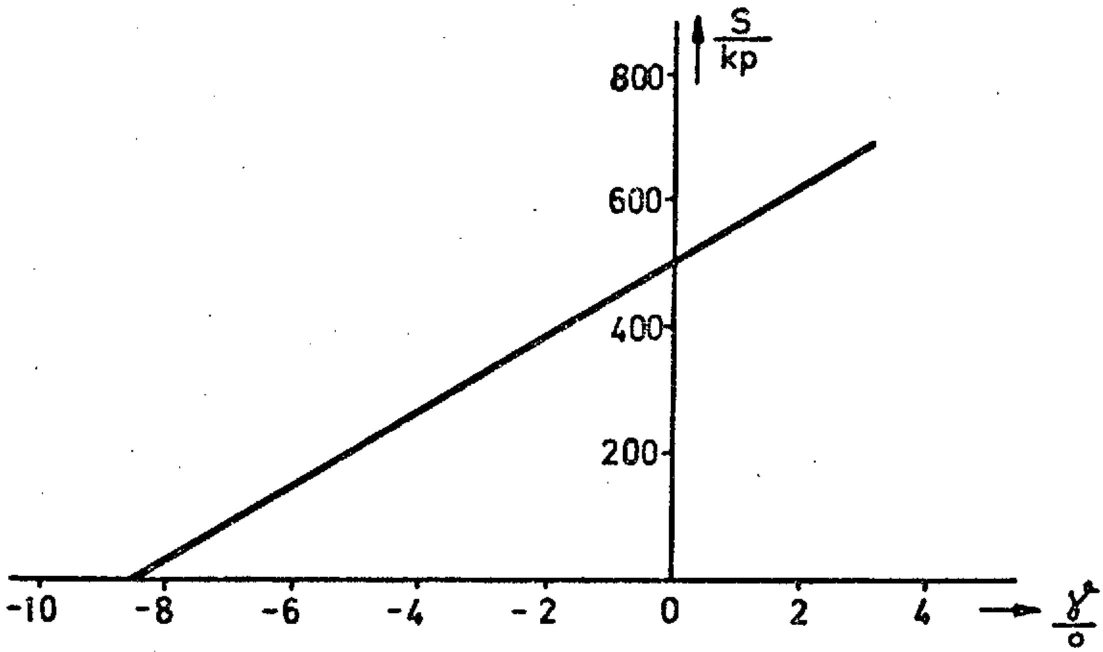

Figure 4. Stationary relationship between trajectory angle and thrust.

thrust for the Do 28 D Skyservant for a ratio of $C_W/C_A = 0.15$ and a weight of G = 3400 Kp. For a transition from horizontal flight to descending flight with a trajectory angle of $\gamma = -7°$, the thrust must be reduced by 400 Kp, corresponding to 60% of the total thrust. From this we find the required regulating factor of S/γ = 57 Kp/0. The investigations have shown that for /9 sufficiently quiet thrust conditions, it is only possible to realize a factor of S/γ = 3 Kp/0. Therefore, instead of the actual trajectory angle, it is necessary to use the nominal trajectory angle with the increased factor of S/γ_{nom} = 57 Kp/0 for thrust control. The nominal trajectory angle γ_{nom} depends only on the prescribed space fixed trajectory profile $H_{nom} = f(R)$ and can be calculated from:

$$\gamma_{nom} = \frac{dH_{nom}}{dR} \tag{2}$$

Figure 5 shows the variation of the prescribed trajectory profile, the associated nominal trajectory angle, and the resulting thrust variation. Since the trajectory profile consists of two straight line elements with two parabolic transition arcs, according to Equation (2), we find a variation consisting of four straight lines for the nominal trajectory angle which transfer to each other without any jumps. It is constant over the straight line segments of the nominal trajectory and in the parabolic transition arcs of the nominal trajectory, it increases linearly or decreases linearly. The resulting nominal value for the thrust for constant C_A values is displaced by the steady state value of the thrust for horizontal flight. Since the steady state value of the thrust in horizontal flight is provided by the integrators of the control system, it is possible to directly switch in a command factor corresponding to the nominal trajectory angle variation for the superimposed thrust control. One possibility of producing this variation consists of obtaining it directly as a function of the distance R using a function generator. The flight control unit GCU 70 built by the Bodenseewerk contains function generators of this type and can be directly used for thrust control.

Another possibility of producing the variation of the signal for thrust control according to Figure 5 consists of numerically determining the nominal trajectory angle. From Equation (2), we find the following:

$$\gamma_{nom} = \frac{dH_{nom}}{dt} / \frac{dR}{dt} \tag{3}$$

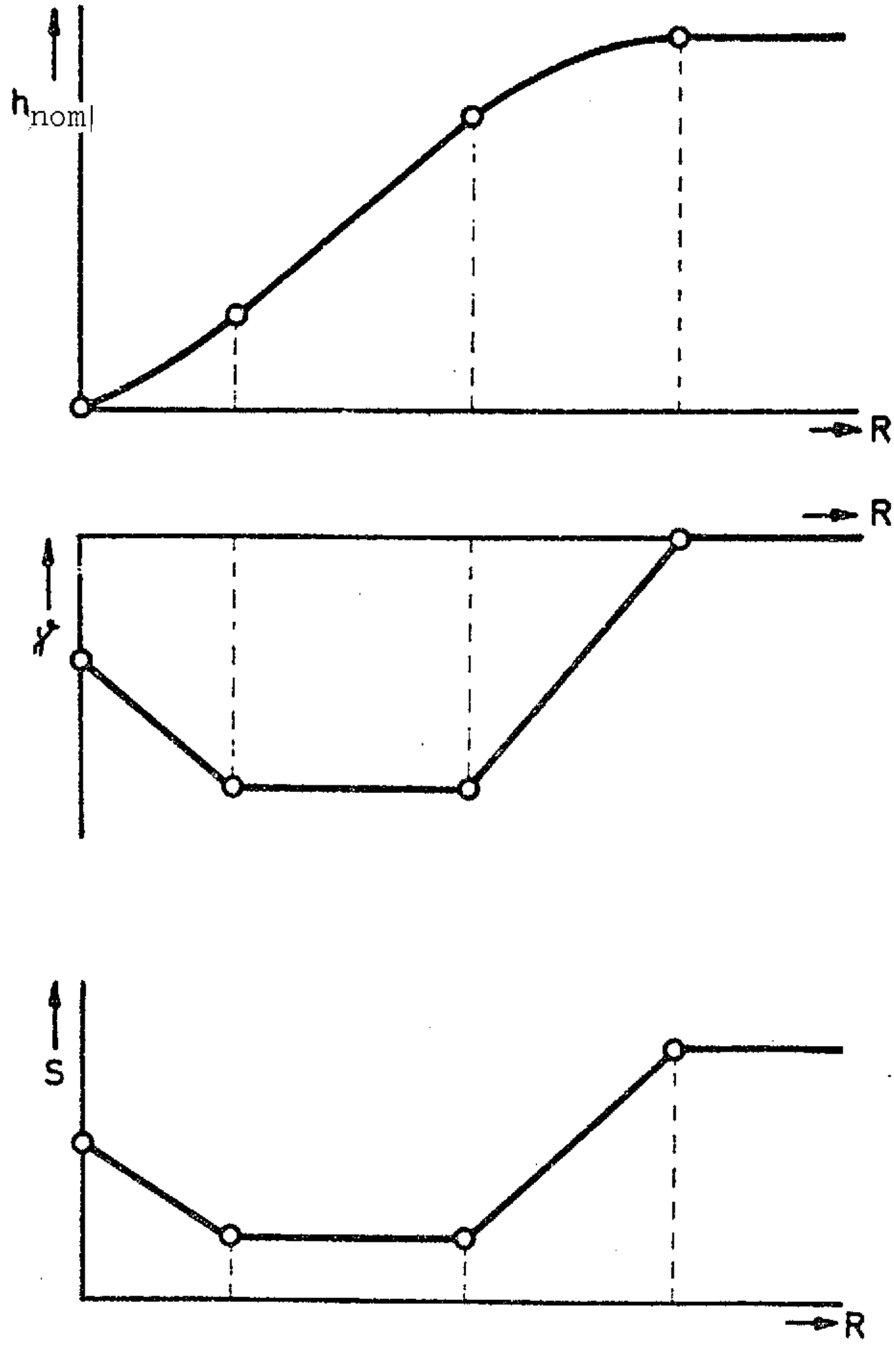

Figure 5. Trajectory variation, trajectory angle variation, and thrust variation for curved steep approaches.

The nominal trajectory variation and the distance variation /10 must be differentiated and divided by each other. Whether or not this system can be realized depends on the accuracy with which these calculation operations can be carried out. The differentiation of the nominal trajectory variation can lead to jumps at the transition points between the individual trajectory elements, if the trajectory profile is not adjusted with enough care. The differentiation of the oblique distance depends on how accurately it has been measured. Finally, the division of these two derivatives can only be carried out with a certain degree of accuracy.

Trajectory deviations for curved steep approaches can occur for two different reasons. Gusts and shear winds can bring about these deviations, as well as the curvature of the trajectory. The only way of avoiding trajectory deviations produced by curvature of the flight trajectory profile is to modulate the nominal trajectory angle. Residual inaccuracies in the thrust control, for example produced by weight changes of the aircraft, are also controlled by the control system, just like the trajectory deviations caused by gustiness and shear winds. By connecting the low thrust modulation of the control signals and by superimposing the thrust control, a behavior of the aircraft is obtained which is characterized by a high degree of trajectory control accuracy and extremely quiet thrust conditions. Figure 6 shows the simulation of a steep approach of the Do 28 D Skyservant guided by a guide beam and for quiet air conditions. The approach altitude is 600 m, the maximum trajectory angle is 7°, and the approach velocity is 65 knots. The good trajectory control brought about by the superimposed thrust control is characteristic for these circumstances, and the trajectory angle and thrust have an identical variation. The angle of attack nominal value is constant during the approach and is increased during automatic

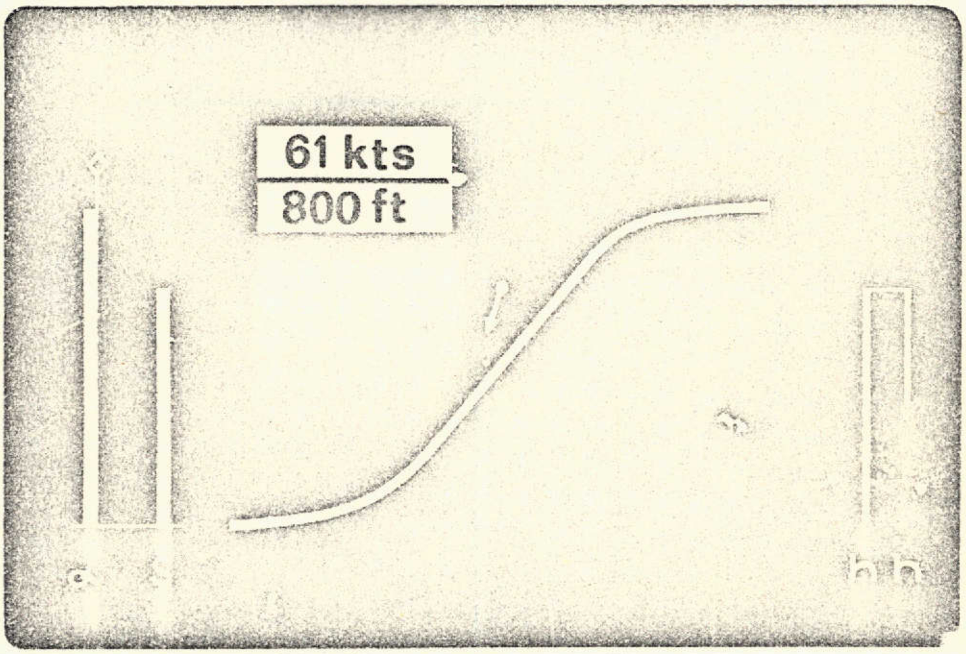

Figure 6. Information display on a monitor display.

pullout. Touchdown occurs at minimum forward velocity and the required safety margin is maintained. The maximum trajectory /11 deviation during the approach is $\Delta h = 3$ m and the maximum angle of attack deviation is $\Delta\alpha = 0.3°$, corresponding to a velocity error of 0.6 knots.

Figure 8 shows the same approach under the influence of gusts and shear winds. The standard deviation of gustiness is one knot, the average opposing wind on the ground is 10 knots, and 30 knots at high altitudes. The shear wind gradient is 6 knots per 100 feet. The shear wind gradient has an especially high value and also produces the maximum trajectory deviation of $\Delta h = 6$ m. We can clearly see the frequency division between the elevator and the thrust, as well as the division between angle of attack and pitch attitude. Because of the low frequency variation of the pitch attitude, a higher degree of passenger

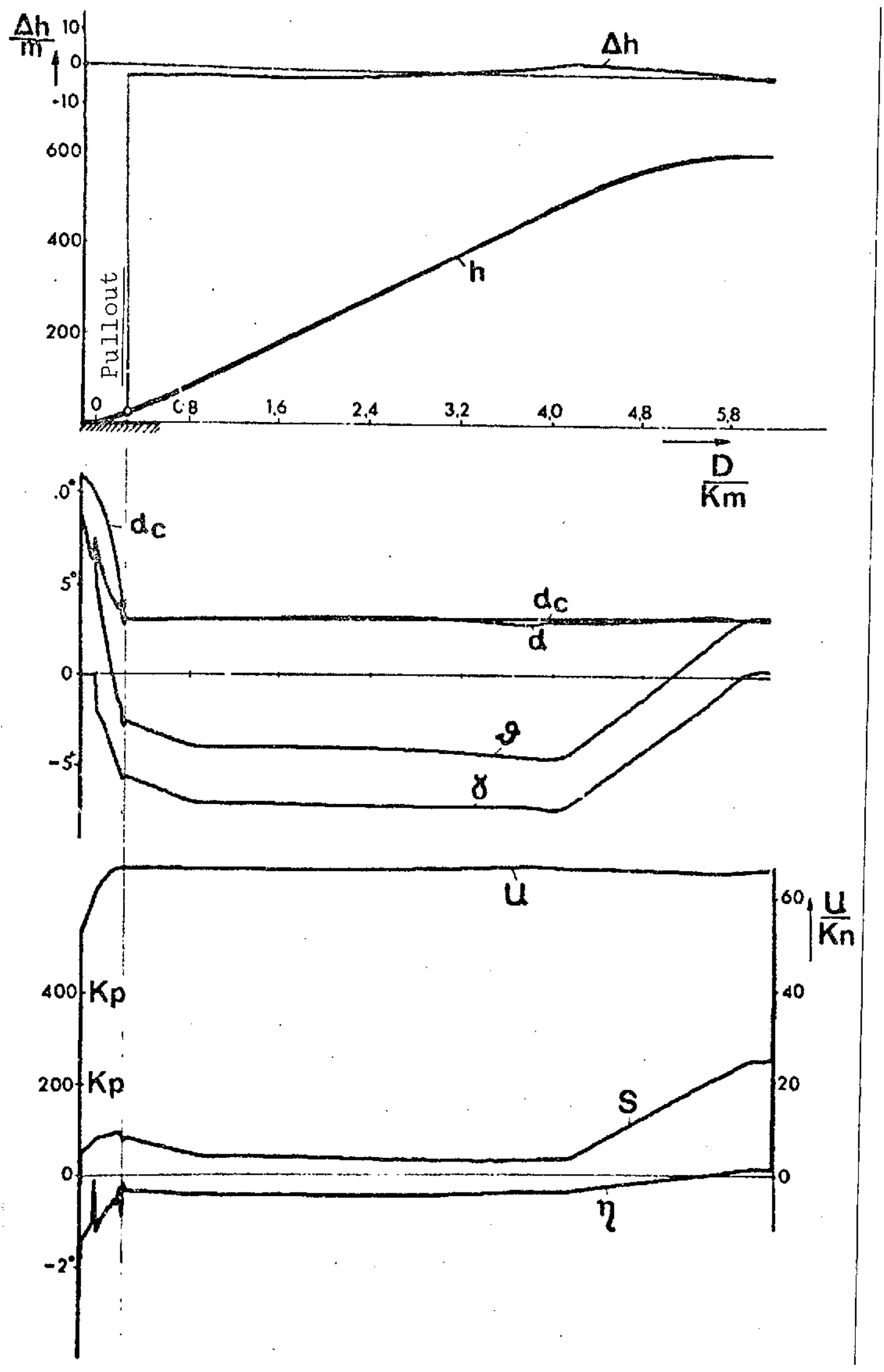

Figure 7. Curved steep approach in quiet air (simulation).

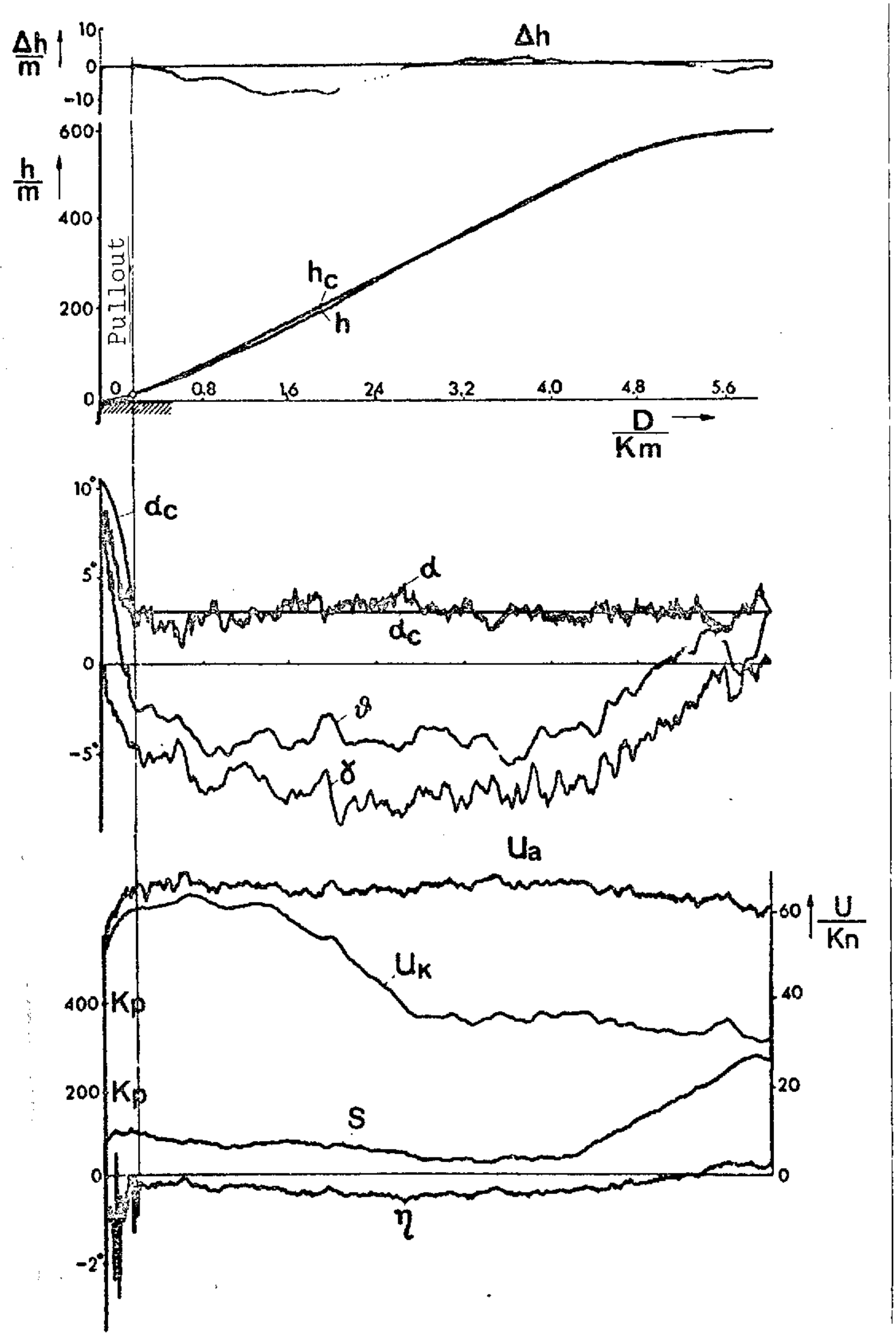

Figure 8. Curved steep approach for gusty conditions and shear wind (simulation).

comfort is provided. Because of the low frequency variation of the thrust, a high degree of thrust quietness is provided as well. Because of the high degree of accuracy of trajectory control and angle of attack control, one finds good flying conditions for curved steep approaches.

5. Elevator Variation for Curved Steep Approaches /12

The elevator variation can be required to ideally follow a curved steep approach profile. This can be done in a manner similar to what was done above for the thrust variation. The pitch moment equation in the steady case ($\dot{\vartheta} = 0$) can be reduced to the following equation:

$$\eta = \frac{c_{M\alpha}}{c_{M\eta}} \cdot \alpha + \frac{c_{My} \cdot l_{\mu}}{c_{M\eta} \cdot u} \cdot \omega_y + \frac{2 r_s}{\rho \cdot F u^2 \cdot c_{M\eta}} \cdot S \qquad (4)$$

In order to provide a high degree of passenger comfort, the flight trajectory curvatures during steep approaches will be so small that the pitch rates which occur will not have a disturbing effect and, consequently, will also not have a significant contribution in Equation (6). Since the angle of attack is held constant during the approach by the integrated control system, the elevator variation according to Equation (4) is only proportional to the thrust. The thrust radius r_s is very important here. In the case of aircraft which have lift flaps which are blown by the propeller jet, r_s can take on sizable values (up to 5 m). In Figure 6 it can be clearly seen that the elevator and the thrust have the same variation. The thrust radius of the Skyservant is about 0.5 m and a maximum of about 1° elevator deflection is required to compensate for this along the prescribed trajectory profile. Because of the favorable design of the controller modulation of the integrated flight control system

FRG 70, no additional compensation line between the thrust and the elevator is required in the case of the Skyservant. In particular, the damper modulation is designed in such a way that it provides good passenger comfort under gusty conditions and it produces the steady variation of the elevator for curved steep approaches. Figures 7 and 8 show that, for flight trajectory curvatures, the elevator and the thrust have to be continuously adjusted.

Since the pilot is only used to changing the thrust in steps, /13
he has a great deal of difficulty in carrying out a curved steep approach for constant angle of attack or for constant forward velocity. Flight tests and simulations have shown that the integrated flight control system FRG 70 satisfies these requirements with a high degree of trajectory control accuracy and angle of attack accuracy by controlling the elevator and controlling or regulating the thrust.

6. Implementation Problems for Complete State Feedback /14

The integrated flight control system FRG 70 is based on the theory of complete state feedback, and control functions are superimposed on the regulation. The main problem is the observation of many states. The description of the system consisting of the aircraft, control elements, and sensors, leads to 28 states in the present case. In an implemented technical flight control system, it is sufficient to obtain the most important state variables. Investigations have shown that, for example, the feedback of the sensor states to improve the quality of the control system contributes nothing and therefore is not required. This cannot be ignored for the controlled element, in general. A stable control operation can only be produced by measuring and feeding back the states of the actuator system, because of the high degrees of modulation on the elevator during the automatic pullout. This can be done by model simulation. In the case of the FRG 70, in the test aircraft Do 28 D Skyservant, this was done by a double differentiation of the rate gyro signal . The states and obtained in this way then provide sufficient modeling of the states of the actuator system.

A further restriction to the theory of complete state feedback in the implemented flight control system FRG 70 is caused by the fact that the beginning of automatic pullout must be free of discontinuities. At the altitude h_s, the control system automatically switches from the guide beam control to radar altimeter trajectory control. The switching altitude increases with descent velocity. The switching condition is:

$$h_s + T_s \cdot \dot{h} = 0 \tag{5}$$

This switching condition makes the variation of the descent arc essentially independent of the descent velocity which the aircraft takes on depending on wind conditions along the guide beam. /15
The theory requires that the radar altitude h_R and its derivative $\dot{h}_R$ are modulated for control during pullout with different coefficients onto the elevator and the thrust. The control laws would be:

$$\eta = K_1(h_R + T_\eta \dot{h}_R) \tag{6}$$

$$S = K_3(h_R + T_s \dot{h}_R) \tag{7}$$

From Equations (6) and (7), it is obvious that the switching at the beginning of automatic pullout can only occur without discontinuities if T_η as well as T_s are equal to the time constant for the pullout condition. This means a restriction in the theory of complete state feedback, because the modulations of the descent velocity state onto the elevator and the thrust can no longer be adjusted independent of each other. Flight experiments have shown that this restriction does not have any noticeable drawbacks and, therefore, it would not be advisable to make the effort of removing this restriction.

7. Direct Lift Control, DLC /16

The integrated flight control system FRG70 can be extended without any difficulty to control the lift flaps in addition to controlling the elevators and the thrust. According to the principle of complete state feedback, the outputs of the observation filters are also strongly coupled and are switched to the lift flap. Whether or not the effort associated with flap control is justified depends on the aircraft properties and the total system requirements. The construction and installation of a sufficiently rapid actuator produces high costs. Investigations have shown that curved steep approaches can be accurately flown with high lift coefficients using the experimental aircraft Skyservant by exclusively controlling the elevator and the thrust. The thrust control depends on the trajectory angle and produces a high trajectory control accuracy and a high degree of thrust quietness at the same time. By additionally controlling the lift flaps, it is possible to increase the thrust modulation and still maintain the quiet thrust.

The high frequency trajectory deviations produced by gusts can be reduced by lift flap control. Flight tests showed that the elevator alone can hold these deviations within sufficient limits. The standard deviations of the altitude difference is about two meters for strong gusts. This value can be reduced by lift flap control. However, we should consider the fact that the altitude deviation can only be calculated with an accuracy of about 2 m from the guide beam data, and the overall accuracy depends greatly on this value. The lift flap control has the advantages of being able to control strong shear winds and to improve the accuracy of the touchdown point. Because higher degrees of thrust modulation are possible using the lift flap control, it is possible to considerably reduce the nominal /17 deviations caused by strong shear winds.

The difference in the touchdown point of the Skyservant using the integrated flight control system FRG 70 without lifting flaps and between quiet air and 15 knots opposing wind amounts to about 80 m. If the specifications require smaller tolerances, they can be maintained by controlling the lifting flaps.

The investigations show that whether or not the effort associated with lifting flap control is justified depends on the requirements and the aircraft type.

8. Information Display /18

The safety associated with a curved steep approach in the case of high lift coefficients can be increased even further if the pilot has an electronic monitor display system available which displays the most important data, instead of the conventional instrumentation. He uses this to oversee the state of the aircraft.

In the case of approaches along curved approach profiles, the pilot must always know his position with respect to the nominal flight trajectory and he must know about the reactions of the aircraft which can be expected during trajectory changes. The nominal trajectory information, the deviation from it, and the flight trajectory direction must be displayed to him, because otherwise, he will not accept such approach conditions, especially for strong gusty conditions. During pullout, because of the large lift coefficients, large angles of attack occur and therefore, large longitudinal attitude angles, which he senses to be dangerous. Therefore, it is necessary to have information on the nominal value, the actual value, and the upper limit of the angle of attack. Since the thrust level is directly connected with the trajectory variation and is also a very important quantity, it must also be displayed.

In order to accurately survey the altitude variation and the resulting descent velocity during pullout, these data are displayed at the beginning of the pullout process. Figure 9 shows a method of display which contains all the required information.

9. Summary /19

The integrated flight control system FRG 70 is based on the theory of complete state feedback. The control variables are highly coupled and are modulated onto the elevator and the thrust. Since, in the case of curved steep approaches, the modulated variables must be continuously changed as a function of trajectory curvature, the pilot can no longer manually carry out these approaches at high lift coefficients and with the required accuracy. Because of the internal coupling, the integrated control system, in contrast to the pilot and conventional

controllers, is in the position of guiding aircraft along curved steep approach trajectories with high lift coefficients. The integrated flight control system was installed in a type Do 28 D Skyservant experimental aircraft. Its properties were demonstrated in over 500 automatic approaches and landings. The design of the control system was carried out using an automatic optimization method, which satisfies as well as possible the requirements according to a quality criterion. By restricting the feedback to the important state variables, a technical version was found which does not worsen the quality of the system.

In the case of automatic approaches with thrust control, the thrust quietness is very important. Quiet thrust conditions are obtained by the internal couplings of the control system, which remove the high frequency influences on the thrust. Since the requirement for thrust quietness does not allow any hard modulations of the regulation variables on the thrust, the high trajectory control accuracy is improved along curved steep approach profiles by means of the thrust control which depends on the trajectory angle.

The competence of the pilot in a flight control system which makes possible curved steep approaches at high lift coefficients can be further increased by suitable information display on an /20 electronic monitor display.

The integrated flight control system FRG 70 satisfies the requirements for trajectory control accuracy along curved steep approach trajectories with high lift coefficients while maintaining quiet thrust and passenger comfort. Therefore, it extends the range over which STOL as well as CTOL aircraft can be used.

10. Notation

/21

c_w	Drag coefficient
c_A	Lift coefficient
α	Angle of attack
$\ddot{x}$	Horizontal acceleration
$\ddot{z}$	Vertical acceleration
ω_y	Pitch rate
h	Altitude
h_{nom}, h_c	Nominal trajectory
h_s	Switching altitude to automatic pullout
$\dot{h}$	Descent velocity
γ	Flight trajectory angle
R	Oblique distance to elevation transmitter
D	Horizontal distance to elevation transmitter
η	Elevator deflection
S	Thrust
r_s	Thrust radius
G	Weight
ρ	Air density
F	Wing area
l_μ	Reference wing chord
u_a	Incident flow velocity
u_k	Flight trajectory velocity

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